Geol. Survey

STATE OF ILLINOIS
DEPARTMENT OF REGISTRATION AND EDUCATION

Radiographic Exposure Guides for Mud, Sandstone, Limestone, and Shale

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CIRCULAR 443 1969
ILLINOIS STATE GEOLOGICAL SURVEY
URBANA, ILLINOIS 61801
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RADIOGRAPHIC EXPOSURE GUIDES FOR MUD, SANDSTONE, LIMESTONE, AND SHALE

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ABSTRACT

The geological X-radiologist must combine four factors that govern radiographic film density to produce a readable radiograph. The relationship of these factors—kilovoltage, exposure conditions, kind of material, and thickness of material—to a desirable film density is shown by exposure guides, which permit the radiographer to select a suitable kilovoltage and exposure for a given sample.

In this study guides were prepared for marine mud, sandstone, limestone, and shale. Individual step wedges of each material were radiographed at different kilovoltages and exposures. The resulting film densities were measured and graphed, thus relating the film density to sample thickness. From these graphs, a film density of 1.5 was chosen and exposure guides were prepared to relate exposure to sample thickness at various kilovoltages.

The isopotential (kilovoltage) lines derived for geological materials are curved, whereas for industrial materials they are straight. This is of special importance to geological radiographers when estimating proper exposure values. Such curved isopotentials indicate that some kilovoltage values, which yield satisfactory results for relatively thin specimens, may give similar results for thicker samples with only a slight increase in exposure time. Other kilovoltages cannot result in properly exposed radiographs regardless of the length of exposure.

The curvature of the isopotential lines is attributed to the porosity of geological materials, and the amount of curvature seems to be proportional to the relative porosity of the rock materials X-rayed. The results indicate

that further studies may greatly extend the usefulness of radiographs in the analysis of earth materials.

INTRODUCTION

Many methods have been devised to enable the geologist to examine the internal composition of a rock specimen. Unfortunately, all have some inherent limitation. Thin sections of rock or impregnated sediment probably give the most complete presentation of structure and composition, but they present only a two-dimensional aspect of a very small portion of the entire rock body. Serial sectioning and point counting overcome this difficulty to some degree, but both methods are laborious and time consuming.

An analysis of rock may be obtained much more rapidly by chemical and mechanical means. Such tests, however, normally require destruction of the sample, and in many investigations, samples represent considerable expenditure of time and money. Some specimens, in addition, are too small to permit multiple tests. In such cases, nondestructive tests, such as X-radiography, may be valuable. Nevertheless, a serious limitation in X-radiographic technique arises from the fact that it essentially records density differences in material and fails, therefore, if factors affecting definition and contrast combine to reduce resolution below certain limits.

This paper reviews the fundamentals of radiology and relates the parameters affecting radiological exposure conditions to geological materials. The exposure guides presented here are not intended for direct application by the reader, but demonstrate what may be expected when similar guides are prepared for a particular X-ray system. For those who wish to inquire further into the principles of radiology, a selected bibliography is provided following the references cited in the paper. In addition, the Appendix gives film densities for radiographs, upon which figures 4-10 and 12-15 are based.

The X-radiographic experiments reported were conducted with a Picker Gemini-160 X-ray machine. The machine produces a constant peak potential and is equipped with an experimental Morris beryllium window X-ray tube. The equipment in the Laboratory of Marine Geotechnique of the University of Illinois was made available by National Science Foundation Grant (GK-1292). The investigations of Gordon Fraser were supported by Office of Naval Research Contract 3985 (09). Nr. 081-260 to Professor Adrian F. Richards, Department of Geology, University of Illinois. Alan James' research was supported by the Illinois State Geological Survey. Mr. Jack Schieb, of Picker X-ray Corporation, and Denny Mansfield, of D. K. Aerospace, were helpful in providing advice on technical problems. Use of a Macbeth Quanta Log Densitometer was kindly provided by D. K. Aerospace, Division of MSL, Batavia, Illinois.

Dr. Charles Collinson, of the Illinois State Geological Survey, and Dr. Richards provided advice and materials during the progress of the research, and along with Dr. W. K. Hamblin and David Ripley, of the Waterways Experiment Station, Vicksburg, Mississippi, carefully criticized the manuscript.

Principles of X-radiography

A radiograph is a record obtained by passing a beam of high-energy electromagnetic X-rays, neutrons, or gamma rays through an object, causing an image

to be formed on a film. As the beam passes through the object, attenuation of the beam occurs because of partial absorption. Passing through a heterogeneous material, the beam is subject to differential absorption, as well as scattering, and becomes more attenuate in the less penetrable areas and less attenuate in the more penetrable areas. A beam of varying intensity emerges from the object and exposes different areas of the film in varying degrees. The result, after chemical processing of the film, is a shadow replica of the heterogeneity of the object.

A variety of radiation sources emit subatomic particles or energy packets, and each is suited to a particular application. At present, neutrons, gamma rays, and X-rays may be used for radiography of geologic materials.

Neutrons can be derived from either reactor or nonreactor sources—only recently have nonreactor sources proved useful, as a result of the development of the neutron intensifier tube, which reduces the size and complexity of the equipment to a practical and economic level (Berger, 1966a). Neutrons are especially useful in making radiographs of thick specimens composed of heavy metals, because such materials are more transparent to thermal neutrons than to X-rays. Neutron radiographic techniques are not suitable for hydrogenous materials because of the high neutron absorption characteristics of water. In special cases where light elements or hydrogenous materials are in combination with the heavier elements, however, neutron radiography may be useful (Berger, 1966b).

Gamma rays originate from the spontaneous decay of radioactive materials and are accompanied by the emission of alpha and beta particles. Differing from X-rays in their source rather than their characteristics, they occupy about the same position in the electromagnetic spectrum as X-rays. The energy and intensity of gamma rays cannot be controlled by the user, because these depend on the nature of the radioactive source and on its rate of disintegration.

X-rays are electromagnetic waves produced by the interaction of high-energy electrons with atoms in a target. The energy and intensity of the radiation is dependent upon the potential existing between the source and the target, as well as upon the temperature of the source. The quality of the X-ray beam is thus controlled by change in the temperature and the potential.

X-rays are better suited for radiography of geologic materials than neutrons or gamma rays. Many geologic materials contain water and, therefore, are relatively impervious to neutron radiation, whereas X-rays easily penetrate hydrogenous materials. Slight differences in density, which are often encountered in earth materials, can best be emphasized on the radiograph by radiation of long wavelength and low penetrating power, which is easily produced by X-radiographic machinery equipped with a beryllium window tube. Gamma rays, however, are emitted over a broad range of wavelengths, depending on the characteristics of the particular source, and are generally of high penetrating power.

Characteristics of the X-ray Beam

An X-ray beam is composed of electromagnetic radiation of a given quality and intensity, the quality being a measure of its penetrating power. The power is controlled by the potential existing between the anode and the cathode of the tube and is measured in kilovolts (kv). Penetration is inversely proportional to wavelength and directly proportional to kilovoltage, so that radiation of short wavelength and high kilovoltage has greatest penetrating power.

Intensity of the X-ray beam is controlled by the tube current (the flow of electrons between the anode and the cathode) and is measured in milliamperes (ma).

Exposure (E) is a measure of the total amount of radiation reaching a given distance in a given length of time. It is thus dependent on kilovoltage, milliamperage, duration of the beam, and distance from the source of the beam. An increase in milliamperage will cause an increase in the intensity of the beam at the same wavelength if the time and kilovoltage are held constant (fig. 1A). An increase in time, with kilovoltage and milliamperage held constant, will also produce a proportional increase in intensity. This relationship is known as the Reciprocity Law. An increase in kilovoltage, however, not only produces an increase in X-ray intensity but also produces rays of shorter wavelength (fig. 1B).

Effects of X-rays on Film

Photographic or film density is a measure of the degree of blackening of an exposed film. It is expressed by the relationship:

$$\text{Density} = \log_{10} \frac{1}{\text{transparency}}$$

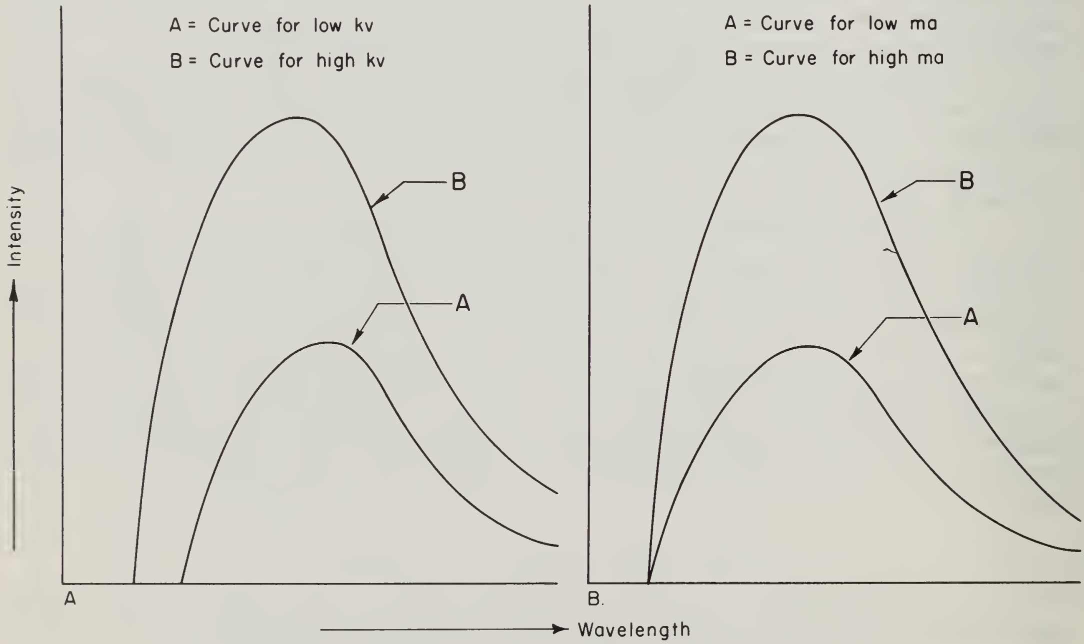

Fig. 1 - A. Increasing the kilovoltage decreases the wavelength and increases the intensity of the beam. B. Increasing the milliamperage increases the intensity of the X-ray beam while wavelength remains unchanged.

where transparency is the amount of light transmitted through a film:

$$\text{transparency} = \frac{\text{intensity of transmitted light}}{\text{intensity of incident light}}.$$

The contrast of a radiographic film is the difference in the film densities of the lightest and darkest regions of the film, or the ratios of their transparencies.

The density of a given film is controlled only by the kilovoltage, exposure, and distance of the film from the source, if there is no material between the film and the X-ray source. If, however, an object is placed between the source and the film, attenuation of the X-ray beam causes two other variables to affect the film density: the type of material, and its thickness. A greater thickness of material will be more impervious to X-rays than a lesser thickness of the same material. Similarly, homogeneous materials of greater density are more impenetrable than homogeneous materials of lesser density. This relationship is expressed by the formula:

$$I = I_o e^{-ux}$$

where

I is the transmitted intensity of the X-ray beam in the same path as the incident beam,
I_o is the incident intensity of the beam,
e is the naperian base logarithm,
u is the total linear absorption coefficient of the material, and
x is the thickness of the material (Gevaert, 1965).

The total linear absorption coefficient, u, is defined by the Bragg and Pierce equation:

$$u = Kt^3Z^3$$

where

K is a proportionality factor dependent upon the specific weight, p, of the material,
t is the wavelength of the monochromatic radiation, and
A is the atomic number of the material (Clauser, 1952).

It may be seen from the immediately preceding equations that short wavelengths of monochromatic radiation experience less attenuation in a given material than long wavelengths.

EXPERIMENTAL PROCEDURE

The exposure guides illustrated here were produced by systematically controlling the variables affecting film density. Rock types and rock thicknesses were controlled by use of step wedges of different rock materials (fig. 2). The wedges consisted of linear series of blocks of marine mud, quartzose sandstone, lithographic limestone, and carbonaceous dark shale, respectively, which varied in thickness by regular increments. Increments of 4 or 5 mm were used because of the relative ease with which X-rays penetrate rock materials. Metals, which are relatively impenetrable, are generally stepped at 0.5 mm intervals.

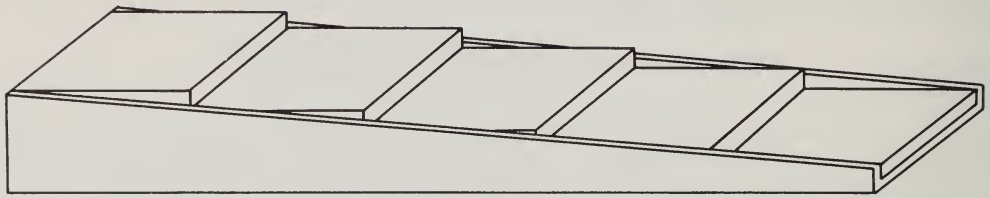

Fig. 2 - Step wedge of limestone used to control rock thicknesses in preparation of the exposure guide.

The step wedges of limestone were cut and ground to the desired thickness. Friable materials, such as the shale (which could not be ground without crumbling), were powdered, placed in a block mold, and compressed to the desired thickness and to the density of the original material. Unconsolidated materials, such as the mud, were placed in a Plexiglas form of the step wedge. The wedges were made approximately 1-inch wide in order to prevent undercut scattering (scattering of the beam under the edges of the wedge), which causes overexposure of the film area beneath the step wedge.

The step wedges were systematically exposed to the X-ray beam at varying exposure values for several series of kilovoltages. Each value produced a series of areas of different film densities on the X-ray film. Each area resulted from the penetration of a particular block by an X-ray beam of a particular kilovoltage and exposure. The film densities (fig. 3) were subsequently measured by a film densitometer and plotted against the variables that produced them on a series of charts preliminary to the final exposure guide (fig. 4).

The preliminary charts thus relate sample thickness to film density.

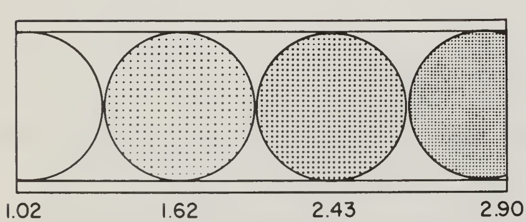

Fig. 3 - Sketch of filmstrip with measured film densities.

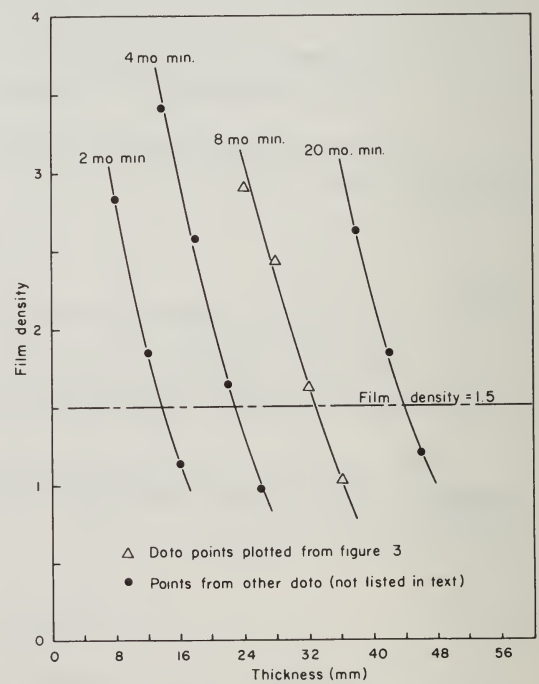

Fig. 4 - Preliminary chart plotting the 8ma min. line from data taken from the filmstrip of black shale on Kodak T film (70 kv) shown in figure 3.

One chart was made for each kilovoltage and consists of a series of lines of equal exposure, with each point on a line representing the film density plotted against thickness for a particular exposure value.

Preparing Intermediate Charts

The intermediate charts, made from a series of preliminary charts, relate kilovoltage to sample thickness for a given film density (fig. 5). The final exposure guide could have been prepared from the preliminary charts, but it was discovered that the use of an intermediate graph compensated for experimental errors such as those occurring in the measurement of the film density and in the determination of milliamperage and kilovoltage.

A given film density was chosen for the preparation of each intermediate chart. This film density was, in most cases, as high as the available illuminators would allow. The characteristic curves for X-ray films show that except for Kodak type F, Ansco High Speed Industrial, and Dupont 504 Pb, industrial films show an increase in film contrast and visibility of detail as the film density increases (Clauser, 1952).

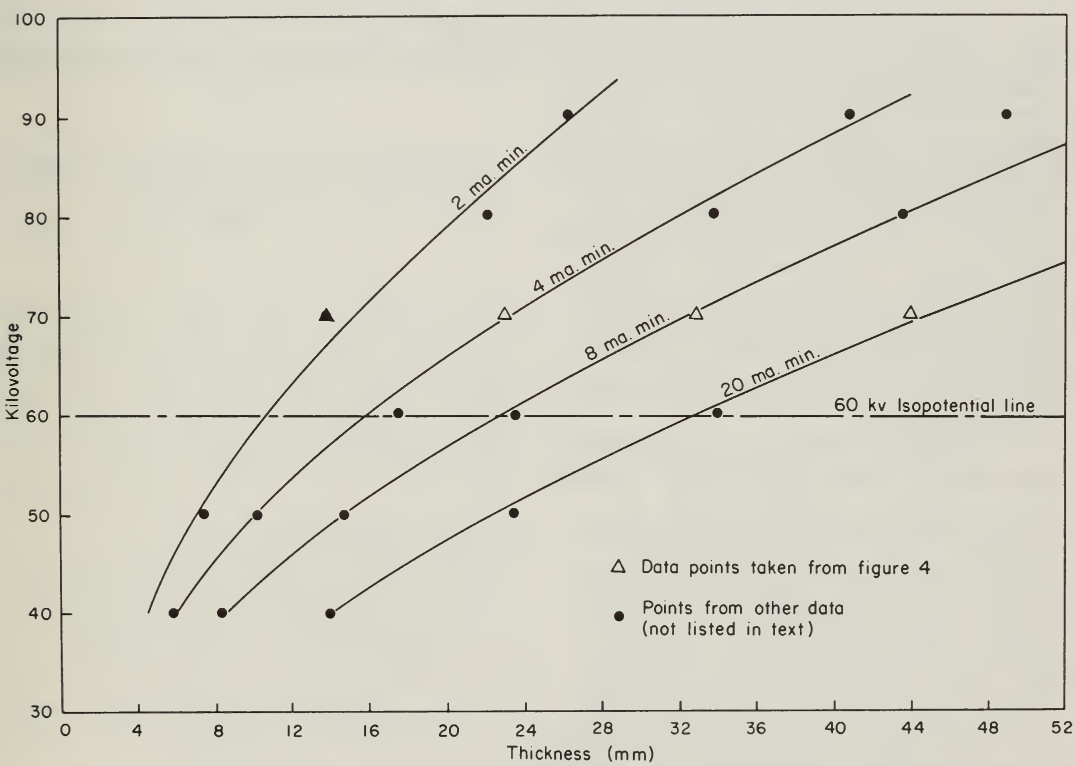

Fig. 5 - Intermediate chart plotted from data on a preliminary chart for black shale. This chart relates kilovoltage to sample thickness for a film density of 1.5, using Kodak T film.

A horizontal line corresponding to the chosen film density was drawn on each preliminary chart (fig. 4), and the point at which this line intersected the isopotential lines (lines of equal kilovoltage) was used in plotting the intermediate charts.

Preparing the Exposure Guide

Inasmuch as the final exposure guide must relate exposure times, sample thicknesses, and kilovoltages, as well as the density characteristics of each particular film, it was necessary to prepare a separate guide for each material and each film type. Each chart was prepared on semilog paper with sample thickness plotted on the arithmetic scale and exposure values plotted on the logarithmic scale (fig. 6). The points at which the horizontal isopotential lines intersected the exposure curves on the intermediate chart were transferred to the final chart and were connected by a smooth, curved isopotential line.

DISCUSSION OF RESULTS

Comparison of Industrial and Geological Exposure Guides

The techniques used in constructing guides for rock materials are very similar to those for industrial radiography. Significant differences in the configuration of isopotential lines, however, require some departures in procedure. In metallurgical radiography, the isopotential lines of the exposure guide are straight when plotted on a semilog chart and, therefore, can be derived from only two data points. As shown by the experiments of this study, however, these lines are curved for many geological materials and require a minimum of three, and preferably four, points for their derivation.

Such curvature in isopotential lines has not been described previously, although W. K. Hamblin (1967) published a series of exposure charts for common rock types wherein the isopotential lines were plotted as straight. Straight isopotential lines were derived from only two points. The fact that isopotential lines in rock materials are gently curved is of great importance for estimating exposures for earth materials and opens a number of avenues for further research in radiographic analysis of earth materials.

The exposure guide for marine mud (fig. 7) shows isopotential lines

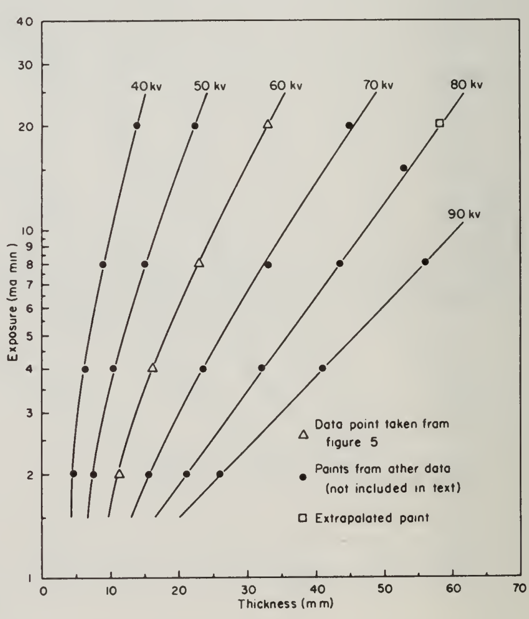

Fig. 6 - Exposure guide derived from data on the intermediate chart (fig. 5) for black shale, using Kodak T film (film density = 1.5).

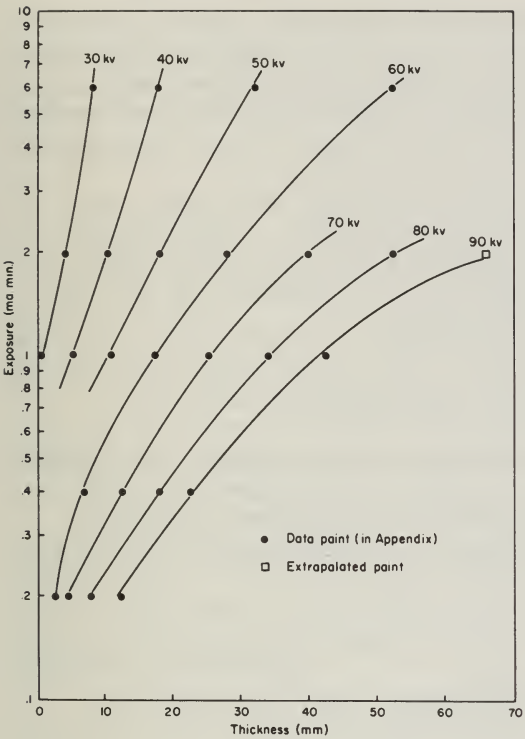

Fig. 7 - Exposure guide for marine mud, using Kodak AA film (film density = 1.5).

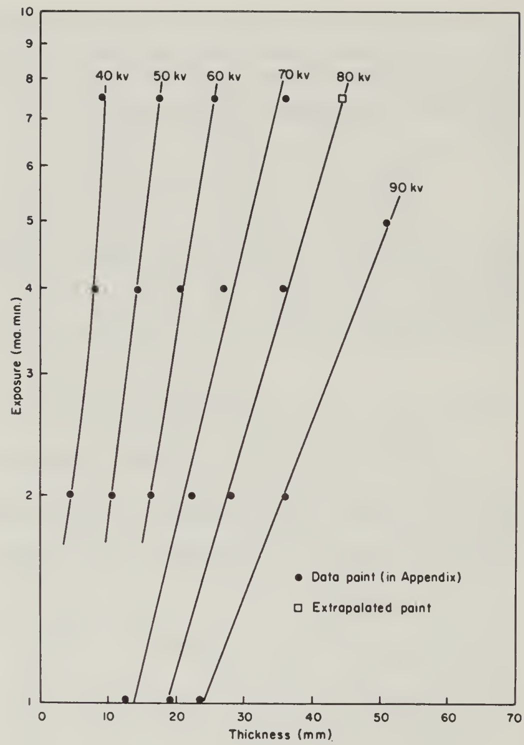

Fig. 8 - Exposure guide for black shale, using Kodak AA film (film density = 1.5).

with values of 70 to 90 kv, which become nearly asymptotic to the exposure values. This indicates that potentials within this range may be used with increasing thicknesses of marine mud with only a slight increase in exposure. It also can be seen that isopotential lines of between 30 and 40 kv curve asymptotically to the vertical thickness values. It appears, then, that for certain specimen thicknesses, these lower kv values cannot result in properly exposed radiographs regardless of the exposure.

In a polychromatic beam, the longer wavelengths will be absorbed more readily with increasing depth in a material than will shorter wavelengths of the same beam. This filtering effect will cause a plot of intensity of an X-ray beam versus depth of penetration of a filtering material to be curved rather than straight, as it would be using a monochromatic beam. However, the filtration effect of homogeneous materials, even at shallow depths, results in the elimination of many of the wavelengths of the polychromatic beam and makes the remaining beam act essentially monochromatic. Thus, the plot of intensity versus depth of penetration generally becomes straight within a few millimeters of penetration. The effectiveness of this mechanism, however, decreases with increasing porosity of the material, and, therefore, it is possible that a plot of intensity versus depth in an especially porous material would remain curved.

This interpretation is substantiated by a comparison of exposure guides for various rock materials. A straight-line function is found for black shale having well oriented clay minerals (fig. 8); slight curvature of the isopotential lines is found for lithographic limestone (fig. 9). Greater curvature of the lines is shown in the guides for quartzose sandstone (fig. 10), and the most radical departure from a straight-line function is found in the marine muds (fig. 7).

Berger and Kraska (1964), using neutron radiographic techniques, have also produced curved-line exposure guides for several metals. They attribute this curvature to neutron and gamma radiation emitted from the material being inspected, however, and such secondary radiation is not thought to have a significant effect at the low energies used in this study.

Limitation in the Use of Exposure Charts

Five basic types of circuitry are available in X-ray machines; each varies in the percentage of peak potential produced during operation (Gevaert, 1965). Exposure guides may not be used interchangeably among different radiographic machines, because depending upon the percentage of peak potential produced by

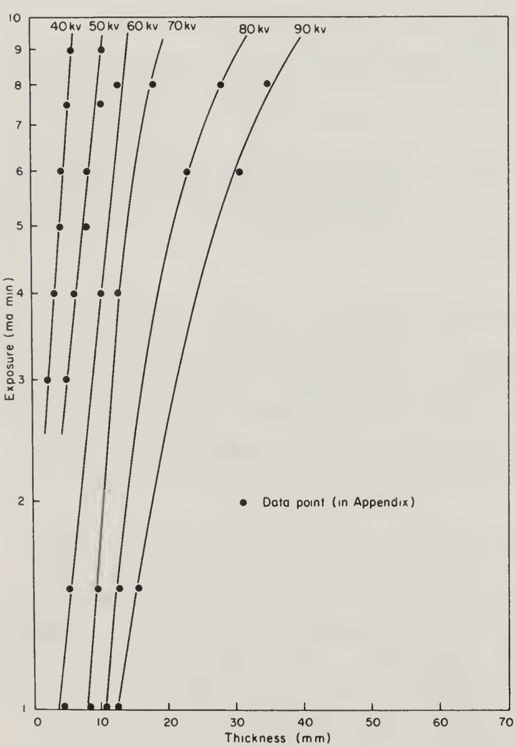

Fig. 9 - Exposure guide for lithographic limestone, using Kodak AA film (film density = 1.5).

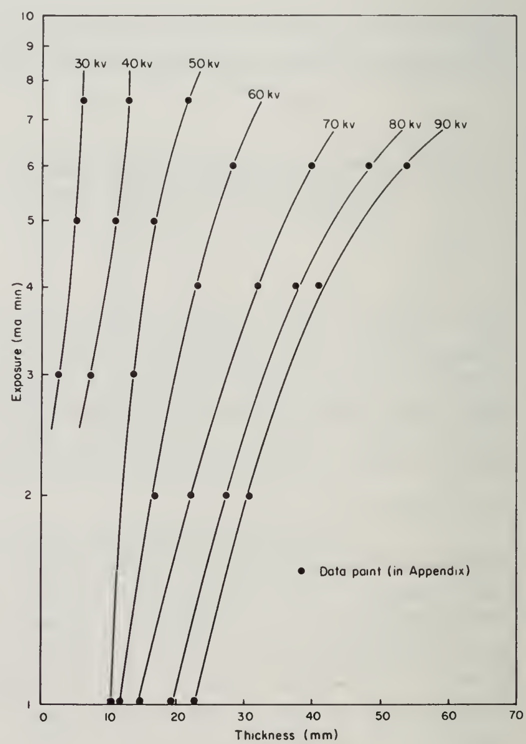

Fig. 10 - Exposure guide for quartzose sandstone, using Kodak AA film (film density = 1.5).

the given machine, different exposure values will be necessary to produce comparable film densities.

The intensity of the radiation per unit area of the film (as controlled by the exposure) is inversely proportional to the square of the focus-to-film distance (F):

$$\frac{I_1}{I_2} = \frac{(F_2)^2}{(F_1)^2}$$

where I_1 is the intensity per unit area at the distance F, and I_2 is the intensity per unit area needed for the same exposure at the distance F_2.

The maximum allowable focus-to-film distance consistent with economical exposure time should be used. This reduces the geometric distortion caused by the divergence of the beam from the X-ray source. The focus-to-film distance used in our investigations was 94 cm.

Different radiographers require different optimum densities, for which their exposure guides are prepared. Consequently, exposure guides for a given film density used in the investigation of some materials may not be suitable for other uses. A film density of 1.5 was used in the preparation of our exposure guides. A darker film may be preferable for many geological materials to give the optimum definition and contrast.

Another factor to be considered by the radiographer is the film type, because films differ in the exposure needed for a given film density. The relative exposure factors given in table 1 are not exact, but vary slightly with different kilovoltages because of the change of curvature of the isopotential lines on the different film types. The radiographer must decide between convenience and definition in choosing the film type, because faster films are more grainy and, thus, reduce definition.

The speed of the film is also affected by the time used for development of the film. Figure 11 shows a change in film speed of Kodak AA film after 5 and 8

TABLE 1 - SPEED AND RESOLUTION CHARACTERISTICS OF X-RAY FILMS
(Symbols under manufacturer's name indicate film-type designations)

KODAK*	FERRANIA	GEVAERT	ANSCO	DUPONT	RELATIVE SPEED	RELATIVE DETAIL
—	—	D2**	—	—	½	Highest
R	—	D2	HD	—	1	Very high
M	I-Gamma	D4	B	510	4	High
AA	IC2	D7	A	506	16	Good
KK	ID	D10	C	—	64	Medium
F	IS2	S	D	504	Very high	Fair
—	—	Super S	—	—	Highest	Fair

*Kodak T film has a relative speed of 8

**Single emulsion

minutes in developing solution. The longer time interval increases the speed of the film by 15 percent, but it also reduces contrast and definition.

Measuring the Film Density

Film density is generally measured on commercial film densitometers. The expense of such an instrument for our study was prohibitive, however, and an inexpensive method for measuring densities was devised.

An S & S model 137A X-ray illuminator, which provides a light source of variable intensity, was coupled with a Variac transformer whose voltage was monitored so that a known and constant light intensity was available at all times. A Knight KG-275A light meter was used to measure the intensity of the light passing through the X-ray film mounted on the illuminator. A calibrated Ansco filmstrip of varying film densities was used to relate the light-meter readings to film densities. This was accomplished by measuring with the light meter the intensity of the light coming through an area of the filmstrip of known density and repeating the process for each different film density on the strip. The light-meter reading and the corresponding film density were plotted on a graph (fig. 12). It was, therefore, possible to determine film density by measuring the light transmitted through a film with the light meter, comparing the meter reading to the graph, and reading the corresponding film density directly from the chart.

The densities of the filmstrips used to prepare the exposure guide for marine mud on Kodak AA film were measured on a borrowed densitometer to check the accuracy of the method. Results obtained from the densitometer were closely comparable to those from the light meter-X-ray illuminator method. Figure 13 shows that the error occurring most frequently is less than 0.04 for

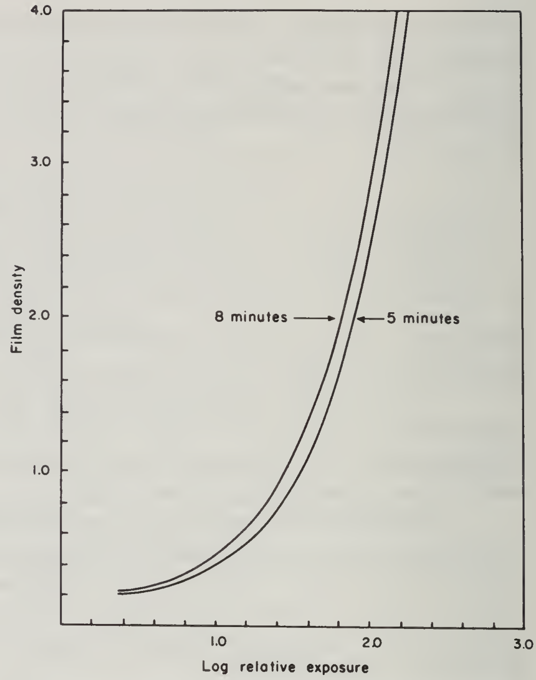

Fig. 11 - Characteristic curves of Kodak AA film after 5 and 8 minutes development (after Eastman Kodak X-ray Division, 1957, p. 109).

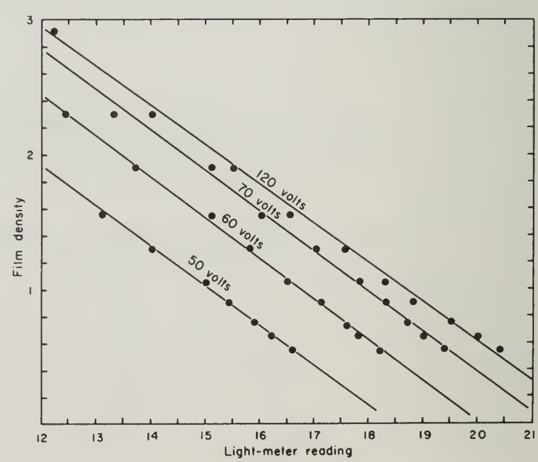

Fig. 12 - Graph of light-meter reading vs. film density for four different line voltages used to operate the X-ray illuminator.

all measured film densities. The curves that were prepared from the densitometer readings nearly coincided with those of the other method, as seen in figure 14.

Relationships Between the Exposure Guides

The relative degree of curvature of the isopotential lines of the exposure guides appears to be a function not only of the porosity, but also of the degree of lithification of the sedimentary materials. The exposure guide for one material may be prepared from that of another if the materials are of similar composition and differ only in the degree of lithification. In the exposure guide for black shale on Kodak AA film (fig. 8), it can be seen that the curvature of the isopotential lines from 40 to 90 kv approximates the curvature in the 40 to 50 kv range on the exposure guide for marine mud on the same film type. A contoured, three-dimensional sur-

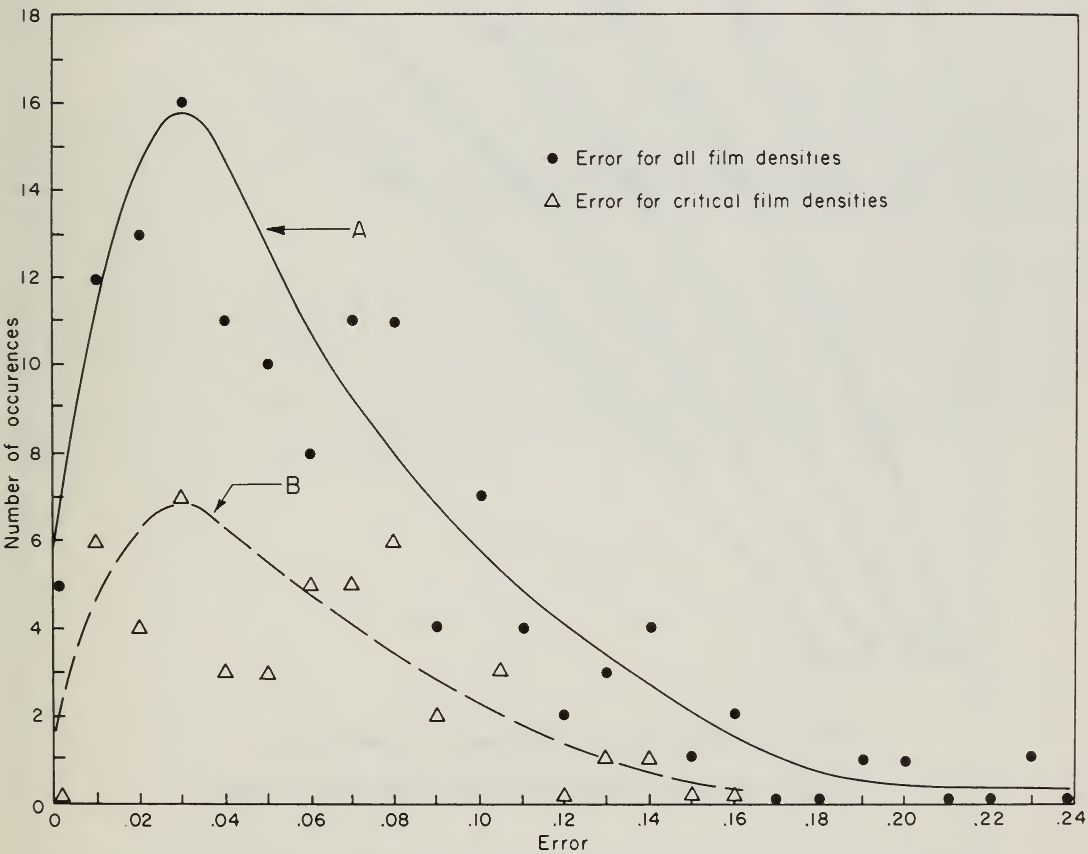

Fig. 13 - Line A shows distribution of error for all densities. Line B shows distribution of error for critical film densities from 0.50 to 1.5. The error shown is the arithmetic difference between the film densities determined by two different methods.

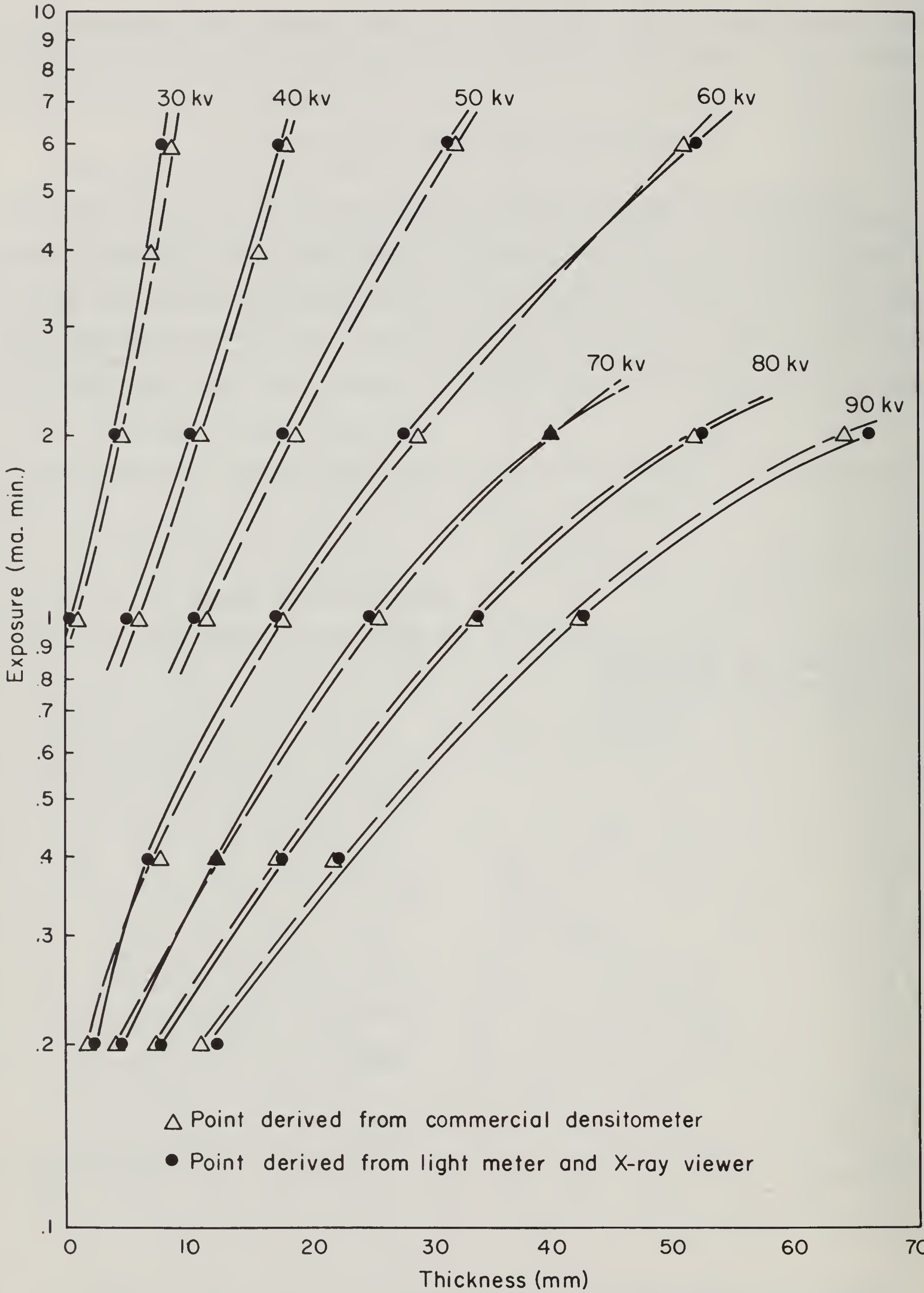

Fig. 14 - Exposure guide for marine mud comparing values derived from use of a commerical densitometer with those derived from a light meter and an X-ray viewer (Kodak AA film; film density = 1.5).

face (similar to a topographic map) of the exposure guide for marine mud, with the kv plotted on the vertical axis, can be prepared. It would seem that the exposure guide for the black shale could possibly be derived from a segment of this surface by comparing the degree of induration of the shale to that of the marine mud.

Materials Used

The exposure guides presented here were prepared for four major rock types. The unconsolidated marine muds were taken from cores collected from the Wilkinson Basin, Gulf of Maine. The quartzose sandstone is from the Ordovician St. Peter Sandstone in northern Illinois. The lithographic limestone is from the Davenport Member of the Wapsipinicon Formation of northwestern Illinois. The black fissile shale is from the Pennsylvanian Modesto Formation underlying the LaSalle Limestone of northwestern Illinois.

SUMMARY

Patchen (1967) determined the exposure factors needed to produce readable radiographs for thin rock slabs of constant thickness. Specimens, however, had to be partially destroyed to produce the thin slabs. We have extended his work by considering the exposure factors necessary for samples of variable thickness. We, thus, hope to re-establish radiography as a nondestructive geological technique.

Exposure guides for geological materials show curvature of the isopotential lines. We attribute this curvature to the porosity of the rock material, because of the correlation existing between the degree of curvature and the relative porosity of the rock materials used. It appears that the relative degree of curvature is also a function of the degree of lithification. The exposure guide for one material may be prepared from that of another if the materials are of similar composition and differ only in the degree of induration.

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APPENDIX

Film densities for radiographs, upon which figures 4–10 and 12–15 are based (using Kodak AA film)

Marine Mud

kv	E*	Thickness (mm)																				
		4	8	12	14	16	18	20	22	24	26	28	32	34	36	38	40	42	44	46	52	60
20	1	.36	.20	.18																		
	2	.45	.23	.18																		
	4	.77	.32	.20		.18																
	6	.95	.41	.24		.18																
30	1	.84	.45	.36		.28		.23														
	2	1.58	.86	.56		.38		.33														
	4	2.56	1.46	.77		.53																
	6	3.46	1.92	1.01		.68																
40	1	1.80	1.02	.74		.56		.44														
	2	3.00	1.96	1.38		.92		.71														
	4		3.35	2.27		1.58																
	6			2.80		2.05																
50	1	2.85	1.92	1.50		.98		.80														
	2		3.12	2.44		1.74																
	4			4.10		3.00																
	6					4.40																
60	.2	1.32	.87	.69		.58																
	.4	1.94	1.56	1.22		.86		.44														
	1											.94			.71				.56		.46	
	2											1.70			22				.84		.62	
	5														2.90				2.28		1.43	.95
70	.2	1.58	1.15	.90		.68		.58														
	.4	2.84	2.15	1.62		1.32																
	1											1.38			.96				.74		.56	
	2											2.56			1.86				1.46		.95	
80	.2	1.92	1.58	1.16		.90																
	.4	3.45	2.78	2.25		1.73																
	1											1.92			1.41				1.02		.77	
	2											3.34			2.70				1.95		1.56	
90	.2	2.55	1.92	1.56		1.19																
	.4	3.97	3.02	2.53		2.01																
	1											2.37			1.86				1.44		.96	
	2											4.20			3.20				2.60		1.84	
Sandstone																						
30	3	1.20	.55	.28		.18																
	5	2.47	.98	.47		.32		.26														
	7.5	2.85	1.08	.53		.32		.18														
40	3	2.86	1.50	1.28		.47		.37														
	5		2.56	1.30		.80		.50														
	7.5		3.30	1.78		.95																

APPENDIX - Continued

Sandstone - Continued

kv	E*	Thickness (mm) 4	8	12	14	16	18	20	22	24	26	28	32	34	36	38	40	42	44	46	52	60
50	3		2.95	1.80		1.28		.80														
	5			2.90		1.87		1.25														
	7.5			4.00		2.55		1.75														
60	1	3.31	2.15	1.34		.93		.65														
	2		3.60	2.44		1.65		1.20														
	4									1.35		1.00	.70		.55							
	6							2.90		2.28		1.43	.95									
70	1	4.25	2.85	1.87		1.40		1.00														
	2			3.43		2.60		1.87														
	4									2.50		1.84	1.45		1.07		.85					
80	1		3.62	2.70		1.94		1.45														
	2					3.54		2.70														
	4									3.44		2.77	2.25		1.71		1.24					
90	1			3.29		2.54		1.84		1.42		1.05	.80									
	2					4.30		3.30		2.54		1.94	1.52		1.18		.85					
	4											3.72	2.90		2.75		1.72					
	6														3.42				2.48		1.69	.99
		Limestone																				
40	3	.83	.30	.18																		
	4	1.19	.39	.18																		
	5	1.78	.62	.32		.25																
	6	1.94	.68	.34		.18																
	7.5	2.55	1.85	.55		.25																
	9		2.85	.86		.36		.18														
50	3	2.35	.83	.41		.28																
	4	2.81	1.02	.58		.24																
	5	3.44	1.71	.77		.58		.49														
	6	4.50	1.92	.86		.47																
	7.5		2.44	1.22		.68		.41														
	9		2.54	1.10		.53																
60	1	1.66	.86	.50		.37																
	1.5	2.25	1.04	.65		.41		.26														
	4		2.04	1.05		.65		.36														
	6												.37		.30		.22		.18			
	8		3.44	1.88		.99				.58		.46										
70	1	2.50	1.38	.80		.56																
	1.5	3.15	1.83	1.01		.65		.47														
	4		3.07	1.85		1.02		.69														
	6									.80		.62	.44				.22					
	8			3.15		1.93		1.08				.84	.64		.43		.31					
80	1	3.25	1.92	1.34		.80		.56														
	1.5	4.25	2.44	1.55		.98		.68														
	6											1.09	.77		.58		.44					
	8											1.51	1.02		.75		.58					

APPENDIX - Continued

Limestone - Continued

kv	E*	Thickness (mm)																				
		4	8	12	14	16	18	20	22	24	26	28	32	34	36	38	40	42	44	46	52	60
90	1	3.83	2.40	1.55		1.01		.68														
	1.5		3.30	2.15		1.35		.92														
	6											1.85	1.34		.96		.59					
	8											2.39	1.78		1.31		.89					
Black Shale																						
40	2	2.60	.90	.45																		
	4	3.50	1.62	.77		.45		.30														
	7.5		2.73	1.02		.60																
50	2	3.80	2.09	1.12		.67																
	4			3.19		1.77		.77														
	7.5				2.27		1.34		.72		.52											
60	2				1.90		1.36		.92		.70											
	4				3.07		2.18		1.36		.86											
	7.5						3.37		2.35		1.40											
70	1		2.70	1.84		1.24																
	2				2.80		2.15		1.49		1.02											
	4						3.43		2.50		1.65											
	7.5											2.97	2.22		1.55							
80	1		3.60	2.56		1.68																
	2									2.37		1.77	1.40		1.08							
	4													2.35		1.84		1.42		1.05		
	6													2.99		2.60		2.00		1.46		
90	1				3.21		2.56		1.87		1.36											
	2									2.89		2.50	1.87	1.40								
	5														3.41	2.75		1.68				

*Exposure value

Illinois State Geological Survey Circular 443
20 p., 14 figs., 1 table, app., 2800 cop., 1969

Printed by Authority of State of Illinois, Ch. 127, IRS, Par. 58.25.

CIRCULAR 443

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